

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE <i>Dec 94</i>		3. REPORT TYPE AND DATES COVERED	
4. TITLE AND SUBTITLE <i>3-D Weather Display for Aircraft Cockpits</i>				5. FUNDING NUMBERS	
6. AUTHOR(S) <i>Bradley S. Boyer</i>					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AFIT Students Attending: <i>Univ of Illinois</i>				8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/CI/CIA <i>94-166</i>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) DEPTMENT OF THE AIR FORCE AFIT/CI 2950 P STREET WRIGHT-PATTERSON AFB OH 45433-7765				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release IAW 190-1 Distribution Unlimited MICHAEL M. BRICKER, SMSgt, USAF Chief Administration				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)					
<div data-bbox="297 1619 755 1732" data-label="Text"> <p>19950117 016</p> </div> <div data-bbox="870 1680 1258 1726" data-label="Text"> <p>THIS QUALITY INSPECTED 3</p> </div>					
14. SUBJECT TERMS				15. NUMBER OF PAGES <i>53</i>	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT		18. SECURITY CLASSIFICATION OF THIS PAGE		19. SECURITY CLASSIFICATION OF ABSTRACT	
				20. LIMITATION OF ABSTRACT	

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3-D WEATHER DISPLAYS FOR AIRCRAFT COCKPITS

Bradley S. Boyer, M.S.
Department of Psychology
University of Illinois at Urbana-Champaign, 1994
Christopher D. Wickens, Advisor

The purpose of this study was to examine the effects of dimensionality and rotating frame of reference in a weather avoidance task. Forty student pilots, performed a 3-D route planning task to navigate around weather formations and arrive at a target within an airspace. The subjects were randomly blocked into four groups, each of which used all four of the display types (3-D rotating, 3-D fixed, 2-D rotating, and 2-D fixed) in varying orders. The subjects performed ten trials for each display type. The results indicated that the 2-D and rotating displays supported navigation through a shorter radial distance, and the 2-D displays also resulted in faster weather planning times. This additional distance and time is attributed to the ambiguity within the 3-D displays. There was no significant difference found between the displays in terms of vertical distance traveled, penetrations of the weather formations, number of vectors created, or the evaluation of situational awareness.

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3-D WEATHER DISPLAYS FOR AIRCRAFT COCKPITS

BY

BRADLEY S. BOYER

B.S., United States Air Force Academy, 1993

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Psychology
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1994

Urbana, Illinois

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE GRADUATE COLLEGE

JANUARY 1995

WE HEREBY RECOMMEND THAT THE THESIS BY

BRADLEY S. BOYER

ENTITLED 3-D WEATHER DISPLAYS FOR AIRCRAFT COCKPITS

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE

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Acknowledgments

The author wishes to thank Dr. Christopher Wickens and for his tireless support and guidance, and Dr. Arthur Kramer for his instruction and input. Further recognition is due to the outstanding programming of the simulation by Ron Carbonari. Also, thanks are due to Rachel Banks and Paul Addotta for there help in running subjects, and Dave Merwin for his assistance in statistical analysis. The author would also like to acknowledge the financial support of the National Collegiate Athletic Association (NCAA) and the Air Force Institute of Technology (AFIT). Research funding was provided by grant NASA NAG 2-308 from the NASA Ames Research Center, monitored by Vernol Battiste.

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Introduction

Every time that a pilot enters the air there are several potentially fatal problems that can occur. One of the most common potential hazards that must be dealt with is the weather. The weather is a factor that is totally out of the pilots control, however it has the potential to make every flight a hazardous one and it is a factor that must be dealt with by all pilots in all classes of aviation. In the field of aviation, weather has been the leading cause of aircraft accidents since the very first flights. According to the Federal Aviation Administration (FAA) weather is the cause of 40 percent of aircraft accidents and 65 percent of air traffic delays of more than 15 minutes. In addition to this, 60% of these adverse weather accidents lead fatalities. The recent crash of an American Eagle ATR-72 in Indiana has been inferred to result in part from both weather related delays and the hazards of the weather itself (icing). For a pilot, there are two phases of dealing with a weather situation: 1) assessing the weather situation 2) choosing an action to deal with this particular situation. This research will concentrate on the first of these, in looking at how the weather information is presented to the aviator.

Weather events that most people would consider irrelevant and not dangerous can be extremely hazardous for the pilot. Weather factors such as thunderstorms and icing have long been known for their potential hazards and have caused numerous accidents. However, since 1975 the majority of air carrier accidents in the US have been caused by windshears associated with microbursts. In particular, between 1975 and 1985 microbursts were responsible for 14 air carrier accidents, resulting in more than 400 fatalities (FAA, 1987) during takeoff and approach, this extreme form of low altitude wind shear can be very hazardous, because the large turbojet aircraft are at or near their performance limits. In a typical microburst encounter, an aircraft, "first encounters a performance increasing head wind. This is followed by a down draft and a rapid transition from head wind to tail wind which produce a sharp loss in altitude and/or airspeed" (Wanke & Hansman, 1992, p.1). This loss of altitude or airspeed may exceed the aircrew's or the aircraft's performance capabilities

Several tragic accidents in commercial airlines have been attributed to microbursts. In 1975, an Eastern Boeing 727 landed short of the runway at New York's

Kennedy Airport, due to a microburst. In the crash ,113 of the 124 passengers died. While in 1982, a Pan American 727 was carried into the ground by a thunderstorm down burst shortly after take off from New Orleans. The resulting crash killed 145 passengers and crew and 8 more individuals on the ground.(Ott, 1985)

Another extremely hazardous weather problem for pilots is icing. One of the factors that make icing layers such a potential problem is that a cloud containing ice looks like any other cloud, and discrimination between safe and unsafe clouds can rarely be made until the clouds are entered and by then it is possibly too late. Icing can occur from two main sources, the first is the result of large drops of supercooled water found in cumulus clouds that can produce fast forming clear ice. The second type of icing can be caused by rain falling from warm to colder air, and will also result in the formation of clear ice. One characteristic of icing, which attenuates its hazard is that icing layers occur in levels that can be flown above or below.

Thunderstorms themselves can also prove to be extremely hazardous for an aircraft. A full bore thunderstorm can have a diameter of up to five miles and can have ceilings as high as 45,000 feet. Some of the hazards that are often associated with thunderstorms include lightning, hail, extreme turbulence, high winds, rain, and microbursts. It is possible to go under or through a thunderstorm cloud when it is still in its building stage, but once it has formed this is no longer an option. Climbing over a thunderstorm is also not advisable in that the worse turbulence is often located at the top.

If the dangers of weather are so well known, one might wonder why pilots venture into these conditions. Studies conducted by Rockwell and Giffin (1987) have examined why pilots continue VFR (visual flight rules) flight into IMC (instrument meteorological conditions). In general aviation, this type of error ranks in the top ten causes for all general aviation accidents (NTSB, 1981). The research showed that part of the reason general aviation pilots find themselves in this extremely dangerous situation is a failure to seek the proper weather information and then to evaluate its risk properly. However, another primary cause was the inability of the pilots to understand the weather information that was provided to them. Thus, even though the pilots had the data, they had difficulty understanding the implications of the weather formations. It is this type of

information that calls for the need to reevaluate the way in which aircrews receive and evaluate weather data.

FAA modernization

Presently, pilots and controllers rely on raw radar returns, surface or pilot observations, and their own experience to interpret weather patterns and make operational decisions. These weather data are provided by the FAA and the National Weather Service (NWS). The current system has been shown to have limitations in both safety and effectiveness. On the one hand, underestimating a weather situation can put aircraft and passengers at risk unnecessarily. On the other hand, error on the side of safety, such as avoiding marginal weather all together, can result in wasted fuel and airspace in the terminal area. (Phillips, 1993). Scanlon (1992) has conducted several studies on the impact of graphical weather products on aircrew decision making, and has found that this combination of air traffic controller input and radar information is very difficult to understand and even more difficult to visualize. Simply because the pilot is looking at a representation of the weather and is simultaneously being described certain characteristics of the weather by the controller, does not ensure that he or she has a good mental model of where the weather formations are and how they are moving. Dash and Crabill (1990) similarly add, that acquiring and assimilating weather information requires a great deal of effort from the pilot, who is usually operating under less than optimum conditions. This information should raise concern, because pilots often make critical judgments based on weather information.

In addition to questions of safety and effectiveness, the present weather information system is limited in three additional ways. First, the forecasts provided for the pilots and the controllers are generated from data that are collected only twice daily. These forecasts are only available in 6-hour increments and are collected from stations that are located 250 miles apart. Both aviators and controllers require weather forecasts that are updated on a more frequent basis. Secondly, the current presentation of weather information is not easily understandable. An example of a weather radar scope and a weather surface map can be seen in figures 1.1 and 1.2. Both pilots and controllers have

other tasks to complete in addition to dealing with the weather, thus this display of information needs to be made more user friendly. "With the latest generation of supercomputers, newly installed weather observing systems, high speed data communications, and modern computer-generated graphics, it is now possible to present weather forecast information in a format that meets user's needs" (U.S. GAO, 1993, p.67). The third problem is that it is very difficult to display all of the necessary information concerning a weather situation on a 2-d display. For example a certain weather formation can only be color coded once. However there may be multiple pieces of information that need to be related to the user concerning each formation (i.e. altitude, intensity, movement, growth rate). Thus, as the information to convey becomes more complex a more complex display may be called for.

In an attempt to provide more up to date and easy to understand weather information, the Federal Aviation Administration (FAA) has set forth a modernization program for which calls for better collection of weather data and improved dissemination of the data to the controllers and pilots (U.S. GAO, 1993). Included in this modernization program are the Automated Weather Observing System (AWOS), the Central Weather Processor (CWP), the Flight Service Automation System (FSAS), and the Aviation Weather Products Generator (AWPG). The purpose of the AWOS is to measure wind velocity, temperature, dew point, altimeter setting, cloud height and visibility through automated sensors. In addition to gathering weather information, the system will be capable of delivering it to the pilots by means of a computer synthesized voice. The CWP uses a Meteorologist Weather Processor and Real-Time Weather Processor to collect, synthesize, and disseminate weather data to the users. The FSAS's purpose is to provide pilots with automated weather data, in particular national aeronautical and meteorological information. It is hoped that this information will increase flight service efficiency and also simplify flight plan filing. Finally, the modernization that is the basis for the present research is the AWPG. The AWPG plans to use the new generation of weather observing systems and the planned NWS super computer. Information will be sent directly to the aircraft through the use of data link, (Kerns, 1991) in the form of alpha-numeric information, or in a display form. Data link will directly connect air traffic

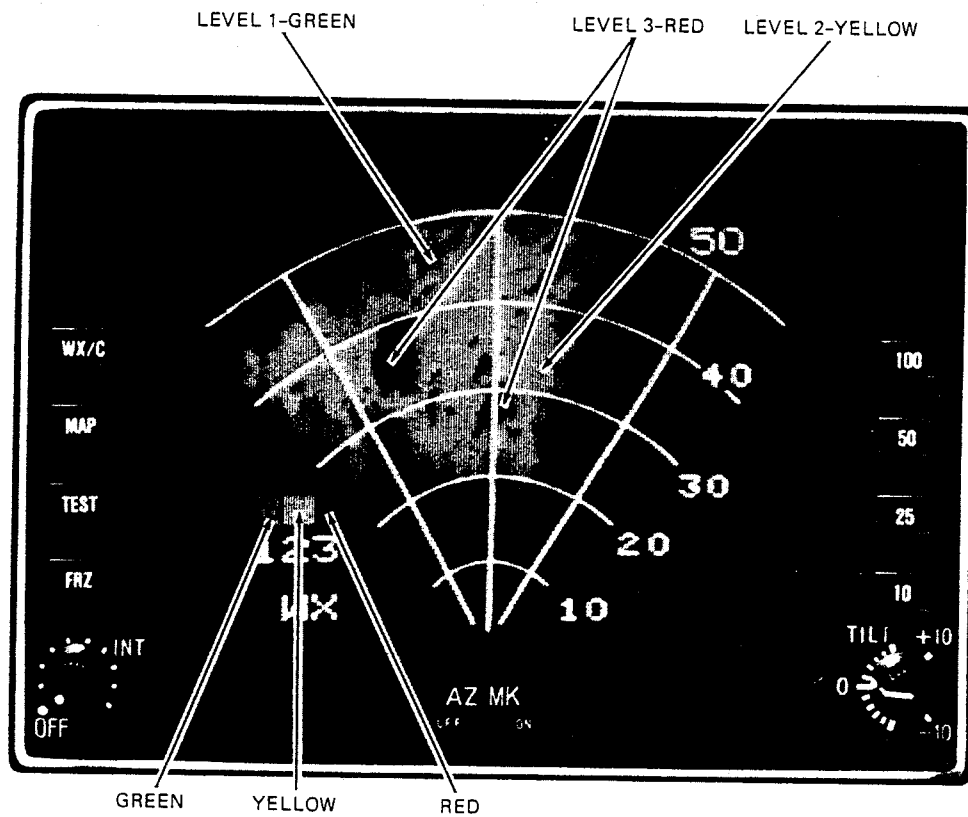


Figure 1.1: Weather radar display, taken from Bent and McKinley (1981)

controllers with the aircraft so that information can be traded through the use of keyboards and CRTs. The use of data link will provide two main advantages. The first is that by having information presented grammatically on a monitor, errors due to miscommunications on the radio will be eliminated. The second advantage is that the system will provide near-real time and short-range forecast depicting hazardous airspace. If careful human factors is applied then the information can be provided in a format that is easy to use, provided by a weather graphics systems.

It is anticipated that by displaying virtually real time information in cockpit displays, pilots would possess a better understanding of the shape and nature of weather formations. A better understanding of weather could increase safety and save the airlines up to \$6 million each year in fuel, time, and rerouting costs due to weather (Phillips 1993). This increased accuracy and more frequently provided weather data would provide pilots with additional information that reduce the task load of flying in poor weather situations. It could also help to reduce some of the tension created between pilots and controllers concerning the avoidance of potential weather problems. However, in order for effective display of real time weather information to become a reality it is first necessary that sensing and assimilation equipment be installed and perfected.

Once the technology of weather sensing has been established, the next question that must be asked is how this information will be displayed? All of the data that will be provided by the new system cannot be converged by the traditional weather displays. Regardless of how well the weather is sensed, if the information is not clearly conveyed to the flight crew then its worth is severely limited. Because of the multidimensional nature of weather, several factors that must be taken into consideration when developing this type of display two of these include: the use of perspective, and rotation of the frame of reference. Whether to use a traditional planar and profile view point or a perspective 3-D view, and the effects of a fixed (north-up) or a rotating (track-up) representation will be addressed in the following sections.

Display dimensionality: 2-D Vs. 3-D

Given that the goal is to display three dimensional (3-D) weather information to the pilot, one key question is whether such a representation is better presented in the 3-D (perspective) or 2-D (planar) renderings. It would seem that the 3-D rendering would be the natural choice for an aviation weather display. Weather is a 3-D phenomena and information about the shape and volume of weather must be fully integrated across all three axes of space to obtain a full appreciation of constraints to navigate within the airspace. Similarly, flying an aircraft is a three dimensional spatial task, that deals in terms of pitch, roll, and yaw of the aircraft as well as the three dimensions of location along the lateral, vertical, and longitudinal (along track) axes. It would appear that a display which integrates these two factors (weather and aircraft state) would best be suited by a three dimensional rendering.

Unfortunately a review of the literature, shows that little or no empirical research has been conducted in comparison of weather display formats. In designing displays for meteorologists, the basic thinking seems to be, that most weather forecasters use 3-D mental models to depict the weather. Thus, since the main purpose of the displays should be to support the development and updating of the mental models, a 3-D display would be the most appropriate (Cechile et al. 1989; Doswell & Maddox 1986). In addition to this, it has been shown that interpretations of cartographic information can be facilitated by using 3-D or perspective representations, relative to flat map-like displays (Bemis et al. 1988; Ware & Beatty 1988). However, the job of meteorologists and the job of a pilot are extremely different and thus may call for different representations of information.

While research examining 3-D rendering of weather for pilots is lacking, there has been a good amount of research conducted in the comparison of 2-D and 3-D displays for pilot navigation. The results have concluded that the nature of a pilot's task will best dictate the type of display that should be used (Wickens 1993). In the process of landing an aircraft the spatial information provided to a pilot must be able to support both a local guidance and a global situational awareness. The local guidance task characterizes the pilot's need to know the necessary direction changes that the aircraft must make to follow the appropriate flight path. This is considered local, because it does not require the pilot

to have knowledge about the airspace outside of the specific flight path. On the other hand, the global situational awareness task characterizes the pilot's knowledge of where the aircraft is in relation to the landmarks on the ground and the elements in the surrounding airspace. Although the global situational awareness task is not needed as often in routine flight, it becomes very important when the flight plan must be altered due to factors such as weather or air traffic. These two tasks have been shown to be differently supported by 2-D and 3-D displays.

3-D benefits In review of the research that has been conducted, 3-D displays have shown to possess two main advantages in performance over the 2-D counterparts. The first advantage is that, integrating information across several spatial locations into one display reduces the amount of visual scanning and "mental gymnastics" that would be needed if more than one view display is used (Wickens, 1992; Wickens, Merwin, & Lin, 1994). In an experiment by Wickens, Merwin, and Lin (1994), subjects viewed complex 3-D data sets and were questioned on their understanding and of the relation across various data points. It was found that the more integrative questions were better supported by a perspective display than a planar display. However, focused attention questions were less well supported by the integrated displays, thus supporting the conclusion that 3-D integrated tasks are specifically supported by integrated displays.

The second advantage is that 3-D displays are more compatible with the way that pilots see the world. Thus, the use of a 3-D display would better support Roscoe's principle of pictorial realism, by providing a view that is closer to the natural view of the pilot (Roscoe, 1968).

3-D costs Thus, the two main advantages of 3-D displays are integration and realism; however, there are several potential costs that have been discovered with the use of these displays. The first cost associated with the use a 3-D display is ambiguity along the line of sight. This refers to the phenomenon caused by depicting a 3-D scene on a static 2-D screen; the result is an ambiguity as to the true position of any point in space (Gregory, 1977). McGreevy and Ellis (1986) refer to this as the *3D-to-2D projection effect*,

resulting from the fact that for a given 2D point within the display there are an infinite number of potential 3D positions. This effect becomes more pronounced as the number of cues for depth are reduced (Wickens, Todd, & Seidler, 1989; Ellis, Smith, Grunwald, & McGreevy, 1991). However, in an experiment conducted by McGreevy and Ellis (1986), when additional cues were provided, two additional problems arose: foreshortening and resolution loss.

Foreshortening or slant overestimation (Perrone, 1992) basically applies to the situation created by the reduction in the perceived depth information in comparison to the perceived display of vertical information (see figure 1.3). Thus, X feet of lateral displacement in the volume may be perceived as X feet of lateral displacement when rendered on the display, but X feet of depth displacement, may be perceived as KX feet of depth displacement (K being less than 1) (Prevett & Wickens, 1994). Therefore, when the user is mentally reconstructing the image, it will appear as if the objects are closer to the display surface than they really are, a fact which creates a “perceptual rotation” of the perceived scene (see figure 1.4). According to McGreevy and Ellis (1986), “this effect can promote overestimation of vertical separations, and will be worsened by increased scaling of the altitude dimension” (p. 455). While foreshortening can be partially compensated for by adding depth cues, the problem of *resolution loss* is more difficult to alleviate.

Loss of display resolution is an effect that is imposed on the human’s basic sensory limitations. Unlike a 2D display, a 3D display will not represent a constant separation of geographical space by a constant distance on the display surface. Thus, “distances orthogonal to the line of sight are represented with greater pixel resolution than those more parallel to the line of sight” (Wickens, et al., 1994, p.5). In other words, resolution loss occurs because when representing an image in 3D space, a change in position of depth, will be perceived as a much smaller change in visual angle, than a change in position of lateral or vertical separation. This resolution loss can cause particular problems if judgments are required for accurate positioning in a tracking task. In addition to degrading the depth changes along the line of sight, loss of resolution will also degrade the perception of the natural horizontal and vertical position of objects that

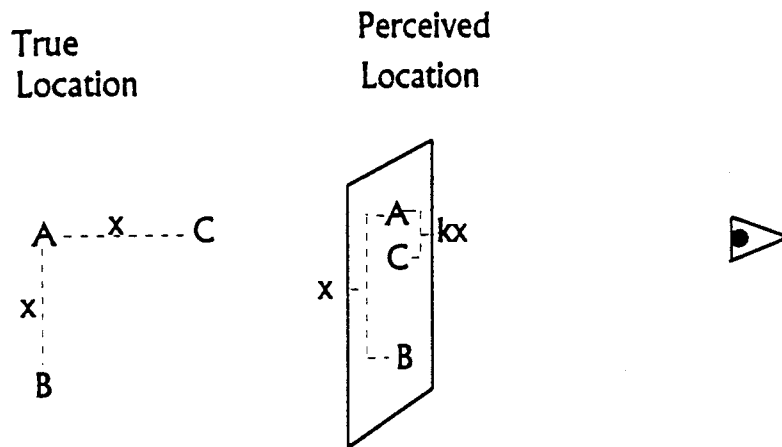


Figure 1.3: Perceived reduction in depth information in comparison to the perceived display of vertical information

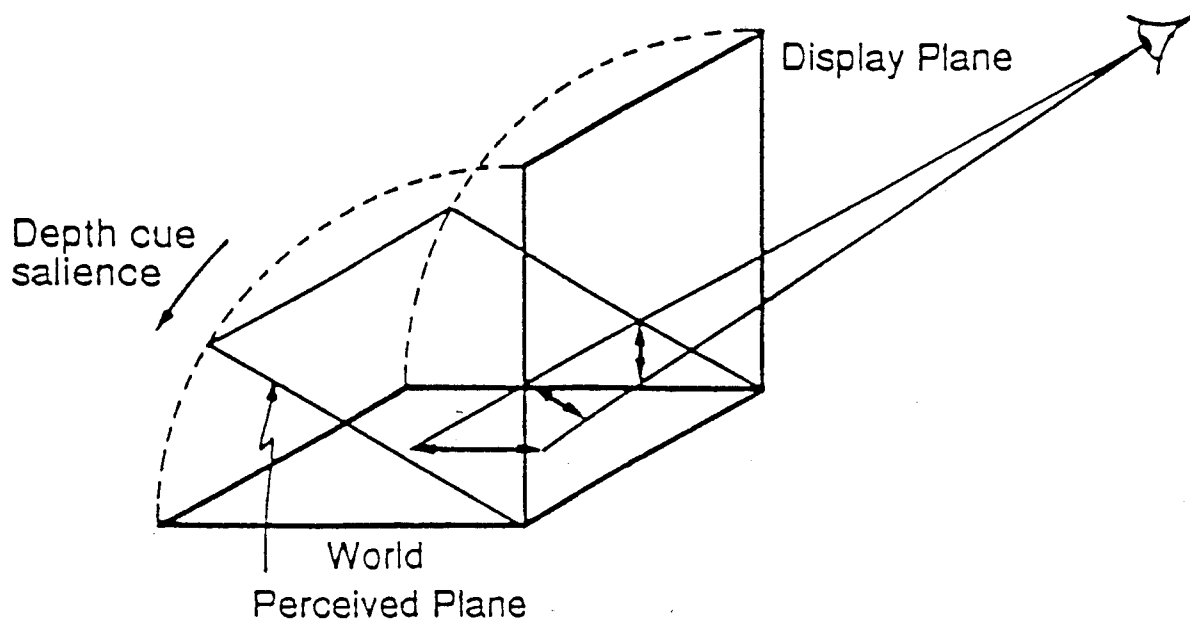


Figure 1.4: Distortion of depth judgments in 3-D displays. Actual distances are subjectively “rotated” to a plane parallel with the viewing plane

are at the “far” end of a perspective display from the user’s viewpoint.

Another potential limitation of 3-D displays is a potential cost of focusing attention on an individual axis. This potential cost occurs due to the integration of information depicting all 3 axes of space into one displayed object. By doing this, it may create a situation where the pilot cannot distinguish change along one of the axes from movement in the other two (Garner, 1974).

Viewing parameters An issue that must be dealt with when considering the use of a 3-D display is that some particular viewing direction must be adopted with regards to the aircraft. McGreevy and Ellis have conducted numerous studies which have examined the geometry of perspective viewing (Ellis et al., 1985; McGreevy & Ellis, 1986; Ellis, 1989). In particular, factors such as the Geometric Field of View (GFOV), elevation angle, and azimuth angle, must be considered. Since these factors are critical to properly representing 3-D information on a 2-D screen each will be discussed.

Geometric Field of View is the visual angle of the image as seen from the view point of the camera, or as defined by Ellis et al. (1985), “the visual angle subtended by the viewpoint as seen from the geometric center of the projection.” Adjusting the GFOV will result in either minifying the world, or magnifying the world (Ellis et al., 1985). Thus, small GFOV angles can be thought of as a telephoto lens, while large angles would be representative of what is seen through a wide angle lens. A bias known as the *virtual space effect* results when the viewing angle adopted does not match up with the actual distance of the view point away from the display screen; a position that is referred to as the “eye station point” (Wickens, Todd, & Seidler, 1989). This incongruence can potentially cause two problems. First the magnification of the scene will cause more real space to be compressed into less display space which can result in distortion. Secondly, if the appropriate GFOV and eye station point combination are not used, the objects seen on the screen will appear to be in a different position than they really are.

Empirical studies have been conducted to determine the effects of altering GFOV. One such study run by Kim, Ellis, Tyler, Hannaford, & Stark (1987) required subjects to track a target with a dual axis Joystick. The GFOV was manipulated between one of five

different angles (8, 12, 28, 48, and 64) while RMS error was measured. It was found that as the GFOV was increased (minification) the subjects' tracking error also increased.

Another study conducted by McGreevy & Ellis (1986) asked subjects to judge the elevation and azimuth angles from a fixed reference cube to a target cube in a perspective display. The GFOV was varied between four conditions (30, 60, 90, and 120) degrees. The experimenters found that the elevation angle was consistently overestimated, especially in narrow field of views. Also, it was found that the smallest overall azimuth errors was achieved at a GFOV of 60 degrees.

Finally, in a study conducted by Prevett and Wickens (1994) GFOV, as well as egocentricity, perspective, and viewing distance, were varied on 3-D displays for a terminal area pilot navigation task. In the experiment the GFOV was varied between four levels (130, 120, 80, and 45) degrees. However, the smaller field of views were matched with longer viewing distances to maintain a constant amount of terrain visibility for all displays. The results showed that the exocentric 3-D display with a GFOV of 120 resulted in a higher mean absolute error in vertical tracking, while the exocentric 3-D display with a GFOV of 45 produced the poorest horizontal tracking performance. It is difficult to make exact judgments on the effects of GFOV in this case due to the fact it is tied to other variables.

Thus, in general it appears as if a smaller GFOV presents an image within which it is easier to determine the relative position of objects in a perspective display. This can be attributed to the fact that the narrower FOV magnifies the scene and provide a better resolution of the distance between objects.

The elevation angle of a display is the angle at which the display "camera" looks at scene in a display. Elevation angle in planar displays are either at 0 or 90 degrees. Angles of 90 degree creates a bird's eye view from above the scene that provides little or no indication of altitude (i.e. other than relative size). On the other hand, 0 degrees conveys only vertical information of the scene, and thus little or no horizontal information is provided. Many of the same experiments described above which investigated GFOV also investigated the effects of altering elevation angle.

Experiments conducted by Ellis et al. (1985) and Kim et al. (1987) both found that an elevation angle of 45 degrees resulted in the most proficient tracking scores. Similarly, in an experiment conducted by Hendrix et al. (1994) in which subjects were asked to make angle judgments between two computer-generated cubes located above a grid plane, it was found that performance was maximized at elevation angles between 15 and 45 degrees. Thus, it appears as if both perspective tracking and position judgment is best supported by a 45 degree elevation angle.

The final factor that must be considered in the geometry of a perspective display is the azimuth angle, or the angle away from the "straight ahead" orientation. Ellis et al. (1985) found that the best tracking performance resulted when the viewing angle was at 0 degrees, or directly behind the object, and the worst performance occurred at 135 degrees. The results produced by Kim et al. (1987), were very similar to these, in that they found the lowest amounts of tracking error produced at -45, 0, and 45 degrees of angle. Finally, in the study conducted by Wickens et. al. (1994), when the azimuth angle was varied between 0 and 30 degrees within a 3-D display, there was no significant performance differences across conditions. From these studies, it would appear that a azimuth angle near 0, would produce the lowest amount of tracking error in a 3-D display, but without substantial performance costs out to angles of 30 degrees.

Thus, in adopting a certain viewpoint when using a perspective display several aspects must be taken into consideration. Three of these factors are GFOV, elevation angle, and azimuth angle. From the research it appears that the best results for tracking and determining relative distance between objects will occur with, a narrow GFOV, an elevation angle near 45 degrees, and an azimuth angle around 0 degrees. However, these are only a few of the considerations that must be examined when dealing with a perspective display. Wickens, Todd, and Seidler (1989) review many ways of implementing 3-D displays and dealing with their limitations.

Aviation-relevant comparisons By looking at the advantages and disadvantage of a 3-D display one can appreciate the difficulty in predicting whether a 2-D or 3-D display would be more effective for the navigation weather task. As earlier stated, research has

been conducted comparing these different formats in aviation settings. Although the results have been varied, it has been determined that task analysis of the pilot is important. In general, 2-D displays tend to support tasks that are dependent on global situational awareness, particularly of layout in the lateral plane (Tham & Wickens, 1993; Williams, 1993). On the other hand, under certain conditions 3-D displays have shown the ability to better support local guidance tasks, as well as 3D integration (Haskell & Wickens, 1993; Wickens, Liang, Prevett, & Olmos, 1994). Several researchers have looked at 2-D vs. 3-D comparison and have drawn a variety of conclusions as to how and when perspective displays may be applicable.

In order to examine if a natural display format might be beneficial for aviation traffic avoidance, Ellis, McGreevy, and Hitchcock (1987) compared a traditional planar display with a perspective projection. The task called for the subjects to detect if a potential conflict situation was developing and if so to recommend avoidance maneuvers. The time to select an avoidance maneuver and the types of maneuvers were recorded. The authors discovered that it took the pilots less time to choose an avoidance maneuver when using a perspective display. They also found that the pilots tended to make more vertical maneuvers when using the 3D display than the planar display, and these maneuvers led to quicker achievement of the required separation. This superior performance in the perspective display was attributed to a more natural and realistic depiction of the scene, and reduced mental integration of information.

Andre, Wickens, Moorman, and Boschelli (1991) conducted a study in which pilots were required to navigate to specific points within a 3D airspace without a flight path. The planar displays consisted of four panels that contained a conventional ADI, a top down map, a side-view profile of the aircraft, and a top down compass. The perspective display was presented from a fixed God's eye perspective and was augmented with a single ADI. The data showed that the pilots were able to reach a greater number of points within the airspace using the planar display. It was determined that ambiguity along the line of sight made it difficult for the pilots to determine when they had arrived at a target when using the perspective display.

In contrast, Haskell and Wickens (1993) found support for the use of perspective displays. This experiment evaluated the local guidance task of flying a curved MLS approach to landing, in order to compare 2D with 3D displays. The subjects were measured on their ability to minimize vertical and lateral deviations from the flight path, and to control airspeed. Occasionally, the subjects were given the global situational awareness task of judging the location and trajectory of an intruder aircraft. The 3D display was viewed by the pilots from an egocentric viewpoint, and thus basically from within the cockpit.

The results of the experiment showed a clear advantage for the perspective display in the control of the vertical and horizontal axes. However, the 2D display was shown to be superior for controlling airspeed. The advantage for the 3D was attributed to the reduced scanning with the integrated perspective display, while the superior air speed control in the planar display was attributed to line of sight ambiguity in the 3D display. Neither display demonstrated superior support for situational awareness task.

Rate and Wickens (1993) examined several issues using a terminal approach task to compare 2D and 3D displays. Employing electronic maps or approach plates, which depicted the area surrounding the airport, the pilots were asked to navigate from either a 2-D or 3-D format. Differing from Haskell and Wickens (1993) the 3-D display which Rate and Wickens employed did not present the display from a fully "ego-referenced" view point. Instead, the display had either a fixed north-looking perspective at an elevation angle of 30 degrees or an ego referenced view depicting the world from behind the aircraft. The 2D display was also rendered in corresponding north-up and track-up versions. The purpose of this was to capture elements of a map in both the 2D and 3D view, thus incorporating the full terminal flight path and the surrounding terrain features.

The results of the study showed that pilots performed significantly better using the planar display in the measures of flight control and judgment. This conclusion agrees with the results of Andre et al. (1991), but contradicts the findings of Haskell and Wickens (1993). This disagreement was attributed to the configuration of the 3D display. By employing the exocentric view, pilots experienced ambiguity along the line of sight, and thus had difficulty determining if the plane was on the flight path. Similarly, as the

distance between the viewpoint and the aircraft increased the smaller resolutions made deviations from the flight path harder to detect. Finally, pilots showed no time advantage for the 3D display in responding to questions designed to assess situational awareness, and in fact demonstrated fewer errors for the 2D display.

A continuation of the study conducted by Rate and Wickens (1993) was carried out by Wickens, Liang, Prevett & Olmos (1994). In hopes of improving the performance of the perspective display, several additions and modifications were introduced. However, the research showed that for tracking in the vertical axis the planar/profile display still supported superior performance, while tracking in the lateral axis was indifferent between the two displays. This experiment also examined situational awareness in several ways, including a position report task and a map reconstruction task. The results indicated that subjects were able to make better world referenced judgments when using the 3-D display, however no significant effect of dimensionality was found in the map reconstruction task.

The study conducted by Prevett and Wickens (1994) extended the use of terminal area navigation to further examine the effects of dimensionality, egocentricity, and of reference frame on local guidance and global awareness. Prevett and Wickens found that a fully egocentric 3-D display, such as that used by Haskell and Wickens (1993), produced lower horizontal and vertical tracking error than did either a planar display or an exocentric perspective displays, like that used by Wickens et. al. (1994). In addition to this the 3-D exocentric display with the display viewpoint positioned at a middle distance behind the depicted aircraft produced superior world-referenced situational awareness compared to the planar or other 3-D displays.

In returning to the weather concept, the question must be asked , what will be the more dominate effect in the display? It is obvious that knowledge of the weather is a global situational awareness task, and thus based on previous aviation research it could be predicted that this type of a weather navigation display would be better supported by a 2-D format. However, weather is a 3-D phenomena that would require integration across display panels if weather was depicted in separate 2-D plan view displays (i.e. a 2-D map and a profile display). According to the proximity compatibility principle proposed by

Carswell and Wickens (1987); Wickens and Carswell (in press), tasks that require integration are better supported by more integrated (3-D) displays, which is supported by Wickens, Merwin, and Lin (1994). In addition to this, depicting weather in a 3-D mode would support a more realistic model for the pilot and would reduce the visual scanning that would be needed if multiple displays were employed. To properly address these tradeoffs between factors, a 2-D vs. 3-D comparison of a weather navigation display is needed, and will represent one focus of the present study.

Rotation

Another issue concerning situational awareness, in the design of an aircraft display is that of rotation. Traditionally, most maps and instrument approach plates have been designed in a north-up fashion, for example the pilot will traditionally clip a plastic approach plate to the control yoke in a north-up fashion. In other words, in a north-up display, the world presented to the subject remains in a fixed position representing the world-referenced frame (WRF). This type of design requires the user to mentally rotate the map in order to have the WRF aligned with the ego-referenced frame (ERF), that characterizes both the view out the cockpit and the axes of control. This cognitive operation can be eliminated with the use of a rotating (track-up) map or display. Rotating maps have been shown to improve the ability to make ERF-WRF landmark comparisons and judge turning requirements, and thus are considered superior for navigational tasks (Aretz, 1991; Rate & Wickens, 1993; Wickens et. al. 1994; Andre, Wickens, Moorman, & Boschelli, 1991).

A great deal of research has been conducted on the effects of mental (map) rotation on flight performance and situational awareness, revealing an advantage to map rotation because of the reduction in mental rotation requirements. However, in defense of fixed maps, Aretz (1991) argued that, due to the fact that north-up fixed maps provide a constant frame of reference, this allows users to better learn world features and create a mental model. Knowledge of these features represents global spatial knowledge, thus fixed (north-up) maps better support global situational awareness.

In the study conducted by Rate and Wickens (1993) the effects of map display rotation on flight performance and situational awareness in landing approaches was examined. The rotating displays were shown to produce better performance in the flight control measures. However, no significant difference was found between the north-up and track-up displays in terms of situational awareness.

Display rotation was also examined by Wickens, Liang, Prevett, & Olmos (1994). Pilots were asked to maintain a flight path and demonstrate situational awareness of the terrain features during a terminal area navigation. Replicating Rate and Wickens' (1993) findings, the rotating display supported superior flight performance, and was not detrimental to the situational awareness task.

In support of Aretz's claim that a fixed map will support situational awareness is the study by Barfield, Rosenberg, Hans, and Furness (1992), who examined pilot flight performance and situational awareness based on frame of reference. The data suggested that the pilot's eye (ERF) display produced shorter flight distances between targets; however, the God's eye (WRF) produced more accurate map reconstructions, an indicator of situational awareness

In examining the research, rotating displays appear to consistently produce more accurate flight performance, than north-up displays. Unfortunately, the exact effects of rotation on situational awareness are still unclear. Substantial data has not been shown to support the idea that fixed maps are superior for situation awareness, or that rotating maps are detrimental in this respect. Further research is needed in this area, the results of which would be of particular importance for the development of future weather displays. This is because, as we have noted, weather displays call for a particularly acute global situational awareness, in order for the pilot to understand the present and future nature of the weather.

The experiment

We have seen that the present weather detection and avoidance techniques used by pilots are less than perfect. However, in the near future the technology will be available to send detailed weather forecast information to the cockpit of an aircraft.

Through a combination of advanced weather detection and assimilation pilots will be able to better deal with potentially hazardous weather factors through more accurate and frequent weather information. However, the question remains as to how this weather information will be displayed within the cockpit so as to allow the pilot to absorb the necessary information while simultaneously conducting the tasks needed to fly an aircraft.

One of the primary areas that must be addressed is the potential use of a perspective or three dimensional display. As discussed earlier 3-D displays possess the advantages of integration and realism; however, they also can be subject to problems such as ambiguity along the line of sight, poor line of sight resolution, cost of focusing attention, and the need to adopt some viewing angle. Numerous studies have been conducted in the aviation setting using perspective display. Most of these studies have consisted of a 2-D vs. 3-D comparison while navigating along a flight path. The present research will examine the task of navigating through space without a flight path while avoiding various weather systems. However, this experiment will not involve a test of flight skills, but instead it will involve a 3-D *route planning* exercise. The scenario will present pilots with information at a static moment in time and ask them to trace a safe route through the weather hazards. In order to complete this task, pilots will be required both to have and awareness of the 3-D configuration of the weather, and an ability to trace the 3-D path through the weather. Our review of the literature suggests that this will be the first experiment to compare perspective versus planar display in a weather avoidance task. With the development of many of the upcoming FAA systems this type of question will need to be answered.

Rotation or frame of reference is an issue that must be considered in the development of a weather display for the cockpit. It has been established that the use of a fixed (north-up map) can produce additional cognitive effort in order to bring the WRF into congruence with the ERF, resulting in the fact that rotating (track-up) displays have shown superior performance for measurements of flight control. However rotating 3-D maps are expensive to implement and the exact effects of rotation on situational

awareness are still ambiguous at best. Hence we will also compare fixed versus track-up renderings of both the 2-D and 3-D map.

Methods

Independent variables

Two variables were manipulated as pilots completed the weather avoidance task. These variables were 1) dimensionality (2-D vs. 3-D), 2) map rotation (rotating vs. fixed world). The design was set up as a repeated measures so all subjects used all possible combinations of display type.

Subjects

Forty University of Illinois student pilots participated in the experiment. Each subject was paid \$5.00 per hour and was tested for approximately 1.5 hours. All subjects were beginning level aviation students with minimum flight experience and flight hours.

Apparatus & task

The study was conducted on a Silicon Graphics IRIS workstation with a 16 inch diagonal screen. The subjects task was to construct a 3-D path around the weather, by creating a series of connected linear vectors, beginning at the origin on the south side of the weather; and ending at a 3-D fix, designated by a point in space on the north side. A two-degree-of-freedom joystick with a trigger in front and a button on top was used by the subjects to trace there planned route and could be placed in the position most comfortable for the individual. The joystick was used to control the orientation of the vector in the xyz space depicting the weather area. A combination of deflections of the joystick and certain buttons allow the user to manipulate the vector with six degrees of freedom. Lateral deflections caused the vector heading to change at a constant rate in the xy plane. For-aft deflections caused a constant rate of rotation of elevation angle of the vector in the yz plane. Pressing the trigger of the joystick projected the vector along the xyz direction established by the lateral and vertical joystick rotation, while pressing the trigger along with the Ctrl key on the key board retracted the vector along that same axis. Once the pilot was satisfied with the orientation and length of the vector he could move the aircraft along the vector at a rapid speed by pressing the button on top of the joystick.

When the aircraft point had reached the end of the previous vector, a new vector was then created to navigate around the weather with its origin at the end of the previous vector. If after the pilot had moved the plane along the vector, he was unhappy with the position of the aircraft, he could backtrack along the vector to the origin (i.e. erase it) and create a new vector. Since, the goal of the user was to reach a marker position on the other side of the weather, the result was a trail left in 3-D space (see figure 2.1). This is not meant to mimic an actual aircraft flying through space, but rather a pencil line indicating a planned route and drawn on a piece of "3-D paper".

Displays

The airspace in which the route planning exercise was carried out was represented by a restricted region of 40x40 miles with a ceiling of 20,000 feet. The weather features were depicted within the area in the form of colored geometric wire frame objects, projecting shadows onto the background (see figures 2.2 and 2.3 for prototypical examples). All trials began with the aircraft in the same location and at the same altitude. There were four different display types: 1) 3-D rotating 2) 2-D rotating 3) 3-D fixed 4) 2-D fixed.

3-D rotating (figure 2.2): In this perspective display subjects viewed the airspace from a 45 deg elevation angle. As the subjects made joystick deflections in the xy plane the world would rotate so that the pilot was always viewing the aircraft from directly behind (azimuth angle = 0).

2-D rotating (figure 2.3): In this planar/profile view, two displays were provided simultaneously on the screen. The upper portion of the screen reflected a planar view of the world to provide lateral information for the subject. The lower portion of the screen depicted a profile view of the airspace, to relay height information to the user. This display used a rotating world, such that the subject viewed the world from directly behind the aircraft.

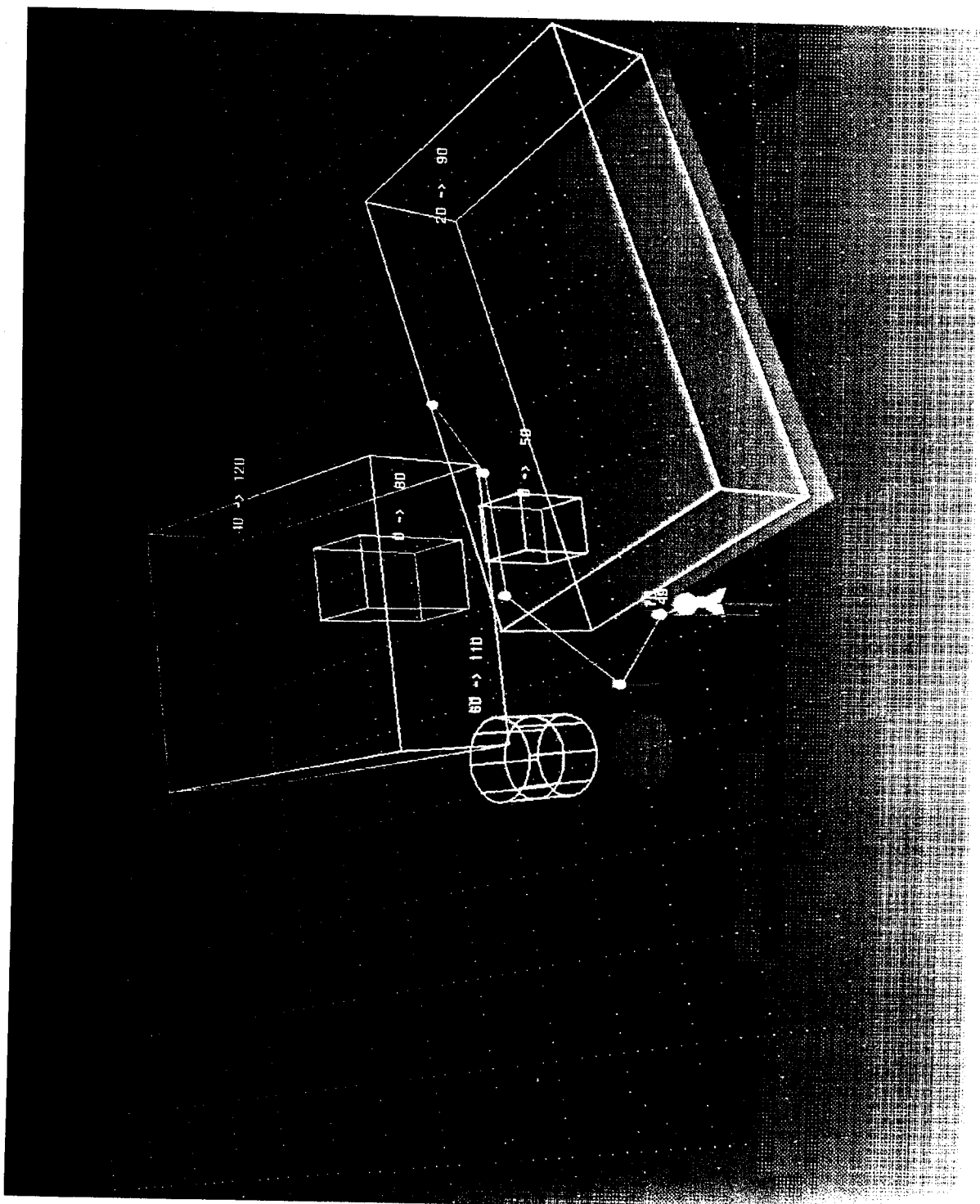


Figure 2.1: Completed trail left in 3-D space, on 3-D rotating display

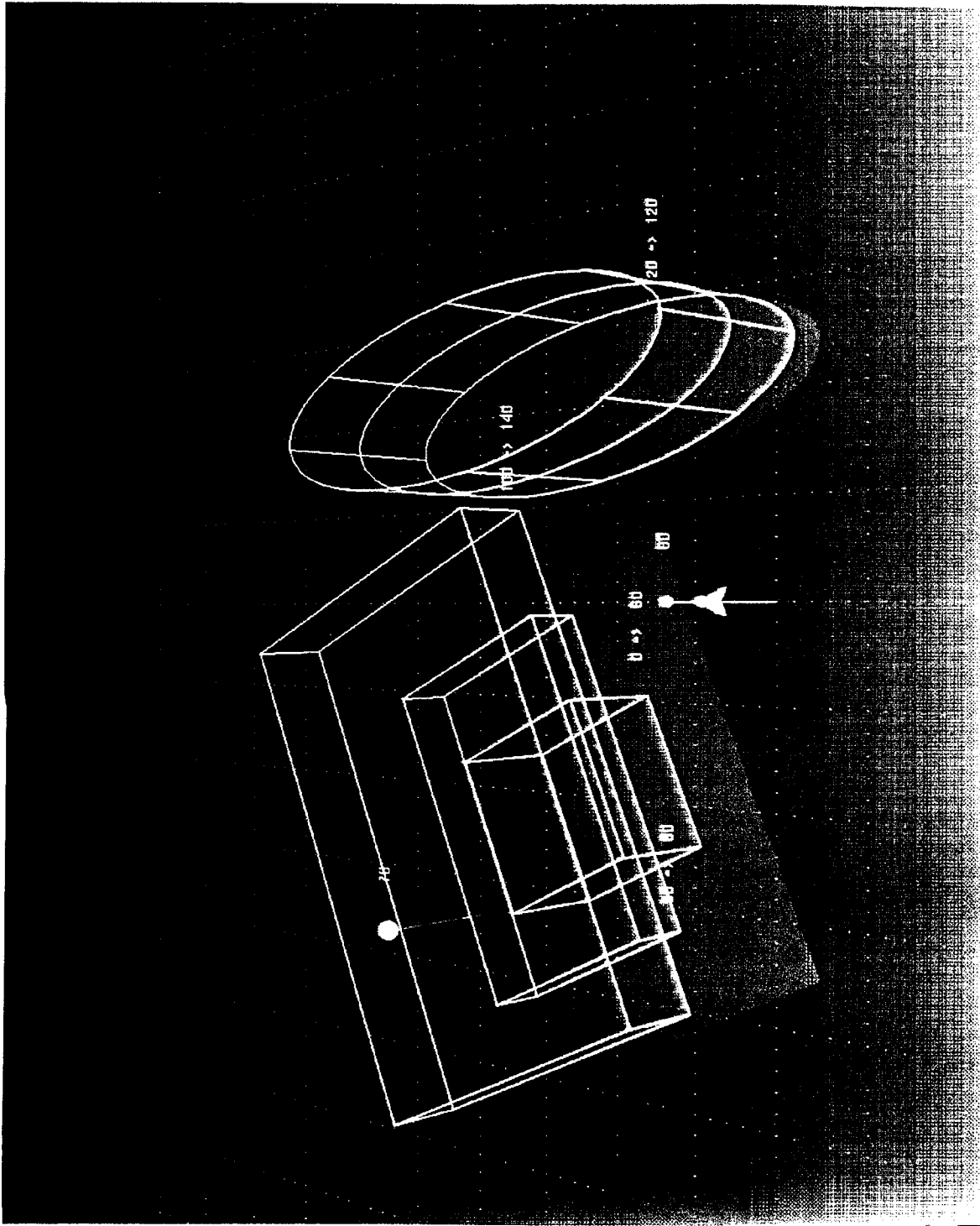


Figure 2.2: Example of 3-D displays

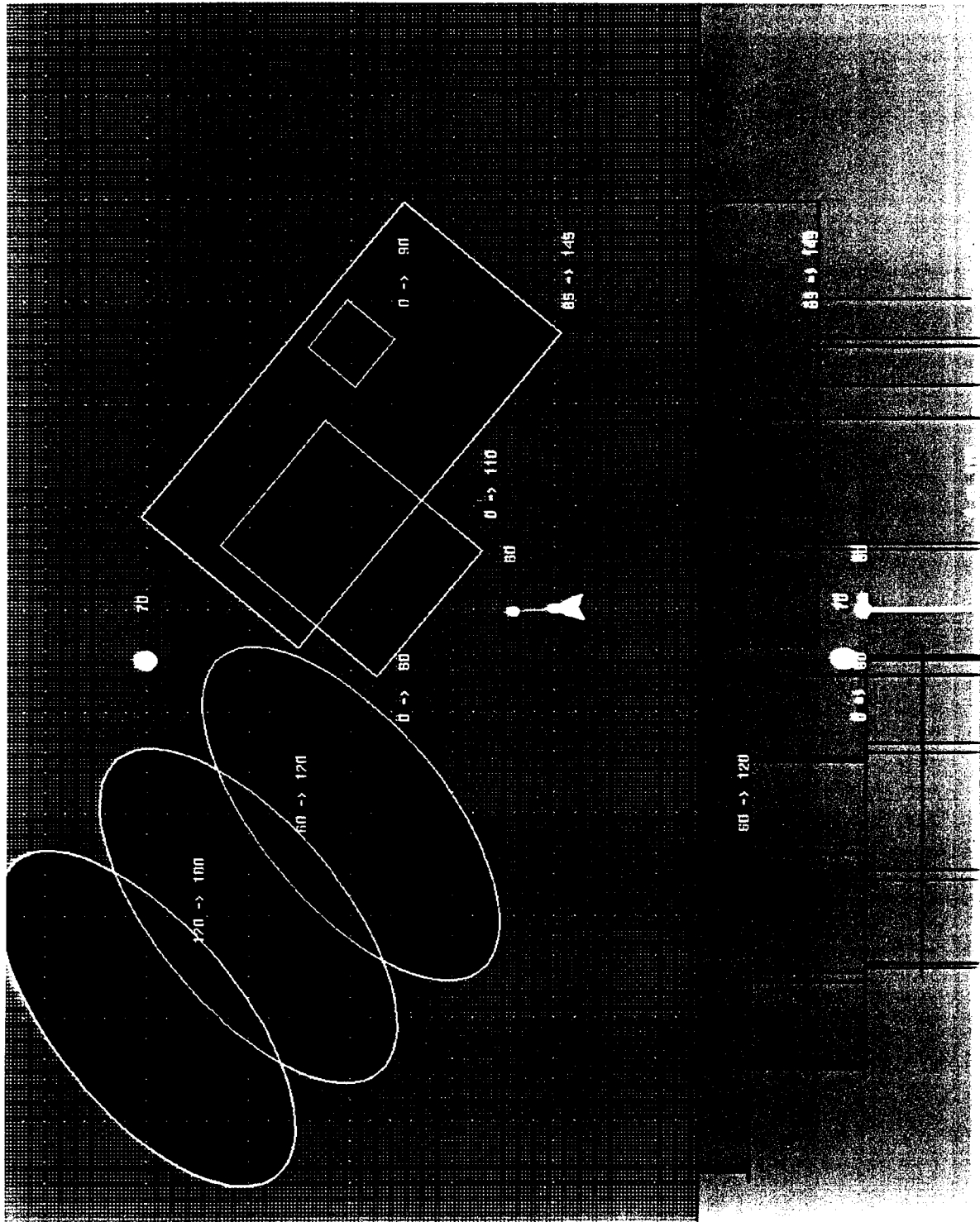


Figure 2.3: Example of 2-D displays

3-D fixed (figure 2.2): This display provided a the same perspective view described in the 3-D rotating display. However, it employed a fixed world view point, where the subject viewed the world from the same north-up orientation for the entire trial, instead of a rotating world view.

2-D fixed (figure 2.3): In this view, the subject was provided with the planar/profile dual screen as described above. However, the view point was fixed as described above.

In all trials the aircraft started in the same location, altitude, and orientation, at the south end of the map oriented to the north.

Features

Several additional features were added to the displays in order to aid the subjects in their weather avoidance task. Most of these features can be seen in figures 2.2 and 2.3.

1) Every item on the display was tagged with a digital reading of its altitude. This included the plane, the end of the vector, the marker, and all weather formations. On many of the weather formations the altitude was represented as a range from the lowest portion of the formation to the highest.

2) The aircraft, end of vector, and marker all had drop lines that could aid in establishing the exact location of these particular items. Used in combination with the grid located on the display ground, these drop lines helped to convey more exact lateral position information in the 3-D displays.

3) If the drop line of the vector or the aircraft itself penetrated a weather formation they would change to the color of that formation along the region of penetration. Thus, this provided information to the subject if they were about to project themselves, or had already projected themselves into a weather formation.

4) In 3-D displays, the weather formation projected shadows on to the display ground that will provide additional location information that can aid in navigation. The shadows on the ground created by the weather formations were representative of a shadow cast by a sun directly above.

5) While using the three-dimensional displays the viewing angled could be altered by plus or minus 15 degrees in order to resolve any ambiguity along the line of sight. This could be accomplished with the use of the cursor keys (↑, ↓)

6) All displays used color depth cueing to aid in the perception of the location of objects. Thus, objects that were located closer to the subject's aircraft were more brightly colored while objects that were more distant from the aircraft would appear a darker color.

Procedure

Upon arrival, subjects were given instructions on what tasks would required of them during the experiment (Appendix A). All participants were informed that their participation was entirely voluntary, and though there participation was greatly valued they could decline to complete the experiment without forfeiture of pay earned up to that time. No subjects declined to participate in the experiment. After reading the instructions, being informed of the nature of the experiment and signing a consent form, subjects were seated in dimly lit separated room where the apparatus described above was located.

Subjects completed four practice trials, one for each type of display that would be used, under the close supervision of the experimenter. The subjects were allowed to ask any questions about the displays or controls of the experiment. The experimenter ensured that the subject understood all possible functions of the controls and the different features of the displays by the completion of the practice trials. It was stressed to the subjects to take the shortest route possible through the weather and to complete the trial as quickly as

possible. The door was then closed and the subjects were provided with an undisturbed and isolated environment in which to perform the experiment. Recorded trials were initiated by subjects in order to provide rest periods between each trial. Each trial took approximately 80-100 secs.

Design

The forty subjects were randomly broken into four groups each of which were randomly assigned to one of four display condition orders. Subjects completed four blocks of ten trials, each block using a different display condition, so that each display was represented equally often at each order. The weather patterns and situational awareness questions remained in the same order through the varying display orders. The analysis employed a 2x2 repeated measures ANOVA.

Performance measures

Radial distance traveled was measured as the lateral distance of the path taken by the subject from the starting position to the end marker. The subjects were instructed not to expend a great deal of time and effort ending exactly on the final marker in that the computer would calculate the final distance from their final location to the marker. Since the subjects were instructed to take the shortest path possible, an exceeding large radial distance would indicate that the subjects were unable to find the shortest route for a given display type.

Vertical distance traveled was measured as the total deviations from the original altitude. Thus, if the subject started at 6000 ft., climbed to 10,000 ft. to vector over a cloud, and then dropped to 3000 ft. to get under a cloud before arriving at the marker, the vertical distance traveled for the trial would be 11,000 ft.

Penetrations of weather formations were recorded for every trial. Thus, this result simply reflects if the subject came into contact with any weather formations or not, while navigating the airspace. Therefore, this measure could be considered a probability

of contacting a weather formation, since there were 10 trials in each condition, the probability measure could range from 0 to 1.0 in increments of .10.

Number of vectors was measured as the number of new vectors created by the subject to navigate the airspace. Obviously, for more complicated weather scenarios more vectors would be required. Also, if the nature of the weather formations were not easily perceived by the subjects more vectors would also be required, thus reflecting the ability of the varying displays to present the weather.

Contact with the ground was recorded as the number of times the subject projected the aircraft along the vector, when the end of the vector was at altitude zero. This variable represents the subjects awareness of their position in the vertical space, based on a given display condition.

Number of deleted vectors was measured as the number of times in a trial that a subjects deleted a vector and returned to the terminal portion of the previous vector. If a particular display resulted in an extreme number of deleted vectors, it would suggest that the display did not present the weather formations in a manner easy to comprehend.

Time to complete the trial was recorded from the time the subject made their first input with the joystick until the time of pressing the Esc key to indicate that they had reached the marker. The subjects were instructed to navigate the weather as quickly as possible, thus exceedingly long trial times indicates difficulty in finding the shortest path or confusion in navigating the weather scenarios.

Situational awareness was assessed at the end of each trial by asking the subjects a question about the altitude or direction of a certain weather formation in the airspace. These multiple choice questions asked the subjects to recall certain characteristics of the display that they had just navigated (example questions can be seen in table 2.4). The questions were presented on a blank screen, with the possible answers underneath to be

clicked on by the subject with a mouse. In addition to being assessed as correct or incorrect, the subjects were also measured on the time to respond to the question. Most of the questions were asked from a world referenced frame (i.e. figure 2.4: 1, 3, 4, 5), however some assessed situational awareness from an ego-referenced frame (i.e. figure 2.4: 2, 6)

Table 2.4: Example situational awareness questions

- 1) What shape was the highest weather formation?
 1. Oval
 2. Circle
 3. Square

- 2) From the starting point, was the highest weather formation in the left or right portion of the screen?
 1. Left
 2. Right

- 3) Were rectangular formations in contact with the ground?
 1. Yes
 2. No

- 4) Was the top of the largest weather formation higher in altitude than the starting altitude of the aircraft?
 1. Yes
 2. No

- 5) Was cylinder formation located at the top of the screen in contact with the ground?
 1. Yes
 2. No

- 6) Was starting altitude of aircraft higher or lower than lowest weather formation
 1. Higher
 2. Lower

Results

Radial distance traveled

Examination of the data showed that radial distance traveled possessed outliers and was skewed. Therefore, trials that fell more than 3 standard deviations (s.d.) away from the mean were removed, and a log transformation was applied to the data to reduce skewness. Of the 1600 trials, 24 were removed due to exceeding values. (3-D fix: 4, 2-D fix: 8, 3-D rot: 4, and 2-D rot: 8). The data was then analyzed in a 2x2 repeated measures ANOVA in the SAS statistical package.

The radial distance traveled in miles is presented in figure 3.1. There was a significant effect for perspective $F(1, 39) = 23.84$ $p < .0001$, showing that the 2-D maps had a significantly shorter radial distance traveled. The effects of rotation were nearly significant showing an advantage for the rotating displays $F(1, 39) = 3.58$, $p < .066$. No significant interaction was found between perspective and rotation.

Vertical distance traveled

Examination of the data showed that vertical distance traveled possessed outliers and was skewed. Therefore, trials that fell more than 3 s.d. away from the mean were removed and a log transformation was applied. Of the 1600 trials, 27 were removed due to exceeding values. (3-D fix: 5, 2-D fix: 5, 3-D rot: 8, and 3-D fix: 9).

The vertical distance traveled in feet is presented in figure 3.2. There was no significant effect found for perspective $F(1,39) = 1.48$ or rotation $F(1,39) < 1$ in this variable. The interaction between these two variables was also found to be insignificant $F(1,39) = 1.48$.

Penetrations of weather formations

The penetration of weather formations was measured as a 'yes' or 'no' variable in the experiment. Thus, the results reflect a probability of contacting a weather formation based on display condition. The penetration of weather formations is presented in figure

3.3. There was no significant effect found for perspective $F(1,39) < 1$, or rotation $F(1,39) < 1$.

Number of vectors

Examination of the data showed that the number of vectors produced to navigate the airspace possessed outliers and was skewed. Therefore, trials that fell more than 3 s.d. away from the mean were removed and a log transformation was applied. Of the 1600 trials, 21 were removed due to exceeding values. (3-D fix: 5, 2-D fix: 4, 3-D rot: 8, and 3-D fix: 4).

The number of vectors per trial is presented in figure 3.4. There was no significant effect found for perspective $F(1,39) = 1.76$, or rotation $F(1,39) < 1$.

Contact with the ground

Of the forty subjects, only three came in contact during any given trial with the ground, none of them occurring often enough in one condition to be considered statistically significant

Number of deleted vectors

Of the 1600 trials, vectors were deleted in only 49 of them. None of these occurred often enough within a given condition to be considered statistically significant.

Time to complete the trial

Examination of the data showed that the time to complete the trial possessed outliers and was skewed. Therefore, trials that fell more than 3 s.d. away from the mean were removed and a log transformation was applied. Of the 1600 trials, 22 were removed due to exceeding values. (3-D fix: 4, 2-D fix: 6, 3-D rot: 5, and 3-D fix: 7).

The time to complete the trial is presented in figure 3.5. There was a significant effect for perspective (reduction of 6 sec, or approximately 6%) $F(1,39) = 8.37$, $p < .0062$, showing an advantage for the 2-D display. There was no significant effect found for rotation $F(1,39) < 1$.

Situational awareness

Accuracy

The situational awareness questions were recorded as a 'correct' or 'incorrect' response. For each subject the mean percent correct was computed across the 10 questions in each condition. There were 34 questions with two responses and 6 questions with three responses, equally distributed across the four conditions, thus chance performance was approximately 47%. The percent correct of the situational awareness questions can be seen in figure 3.6. There was no significant effect found for perspective $F(1,39)=1.42$ $p<.2403$, or rotation $F(1,39)<1$.

Response time

Examination of the data showed that the time to answer the situational awareness questions possessed outliers and was skewed. Therefore, trials that fell more than 3 s.d. away from the mean were removed and a log transformation was applied. Of the 1600 trials, 19 were removed due to exceeding values. (3-D fix: 4, 2-D fix: 5, 3-D rot: 5, and 3-D fix: 5).

The time to answer the situational awareness question is presented in figure 3.7. There was no significant effect was found for perspective $F(1,39)=1.76$, $p<.1928$ or rotation $F(1,39)<1$.

The ability to alter the viewing angle plus or minus 15 degrees was evaluated as not being a factor. Each subject ran 20 3-D trials where the ability to manipulate the viewing angle was available. On average, the subjects used this function less than twice in these 20 trials.

Although formal subjective ratings were not taken, informal comments made by subjects after the experiment suggested that they preferred using the 2-D rotating display. They reflected that the 3-D displays were difficult to "understand" or were "confusing" and that the fixed displays sometimes left them in a viewing position such that they couldn't tell their exact relationship with the weather formations.

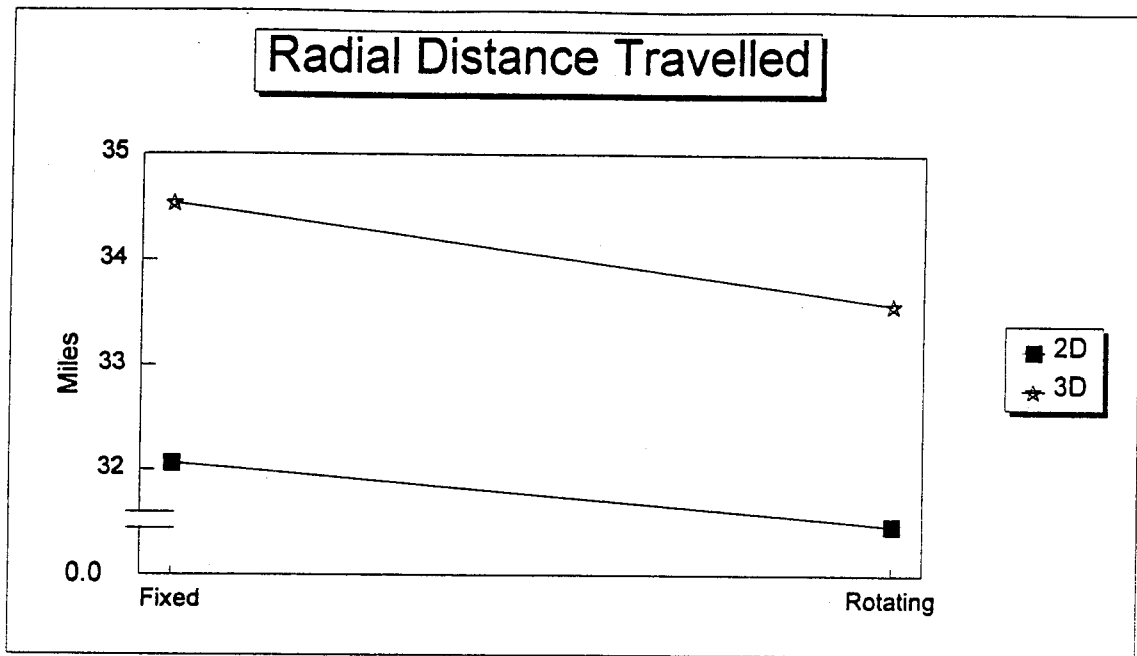


Figure 3.1: Radial distance traveled for each condition type

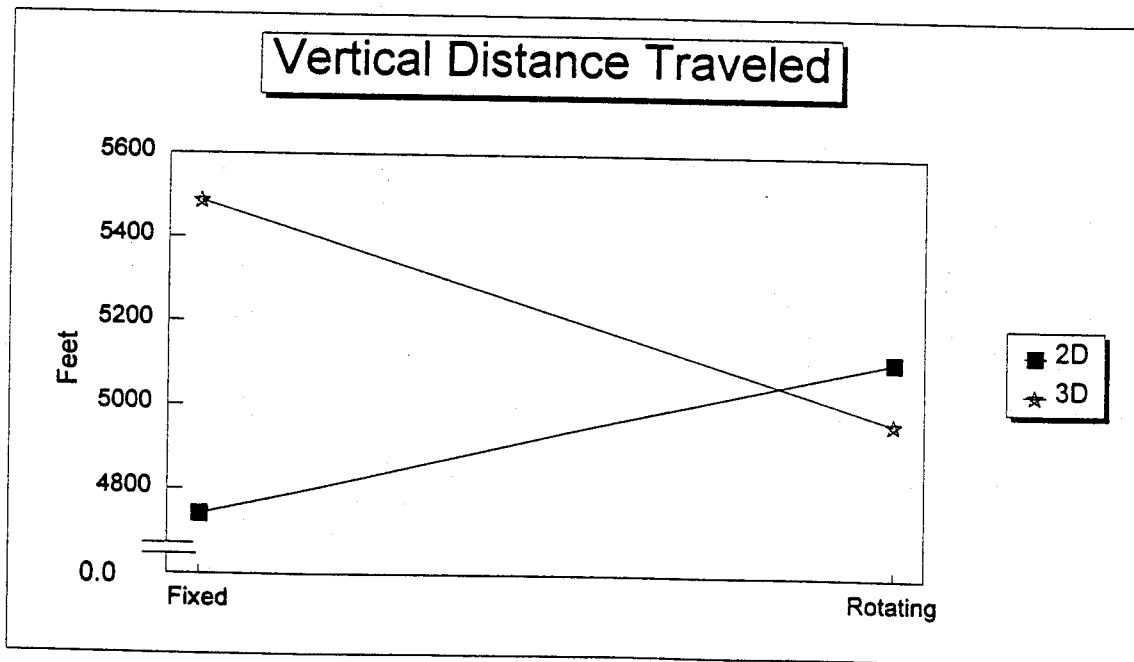


Figure 3.2: Vertical distance traveled for each condition type

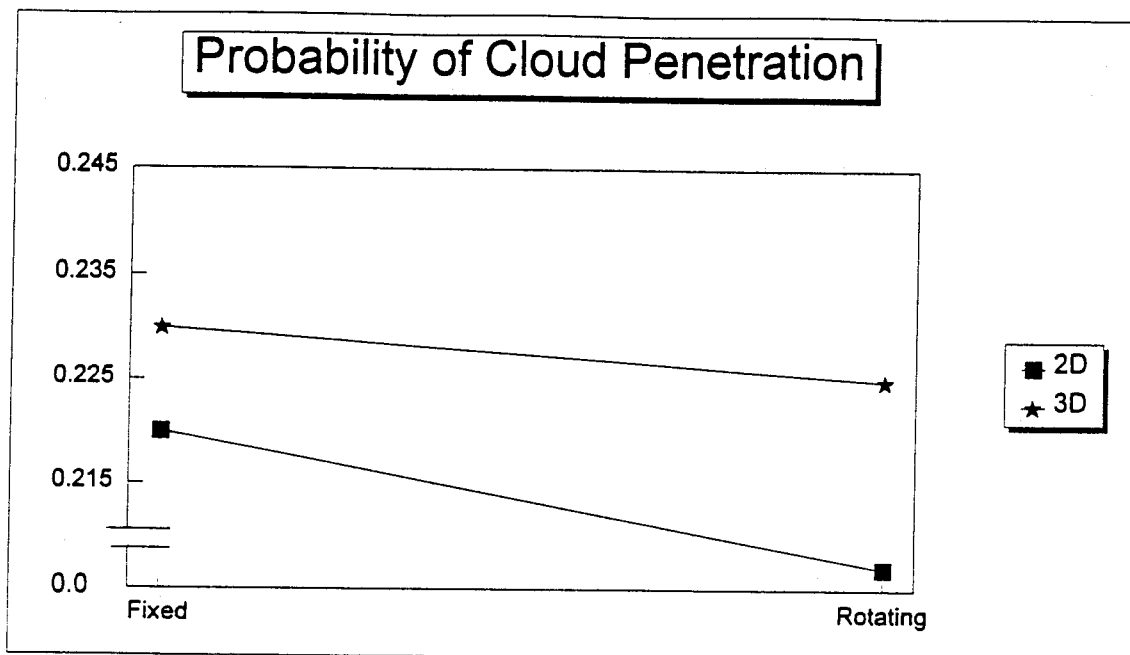


Figure 3.3: Probability of collision with weather formation

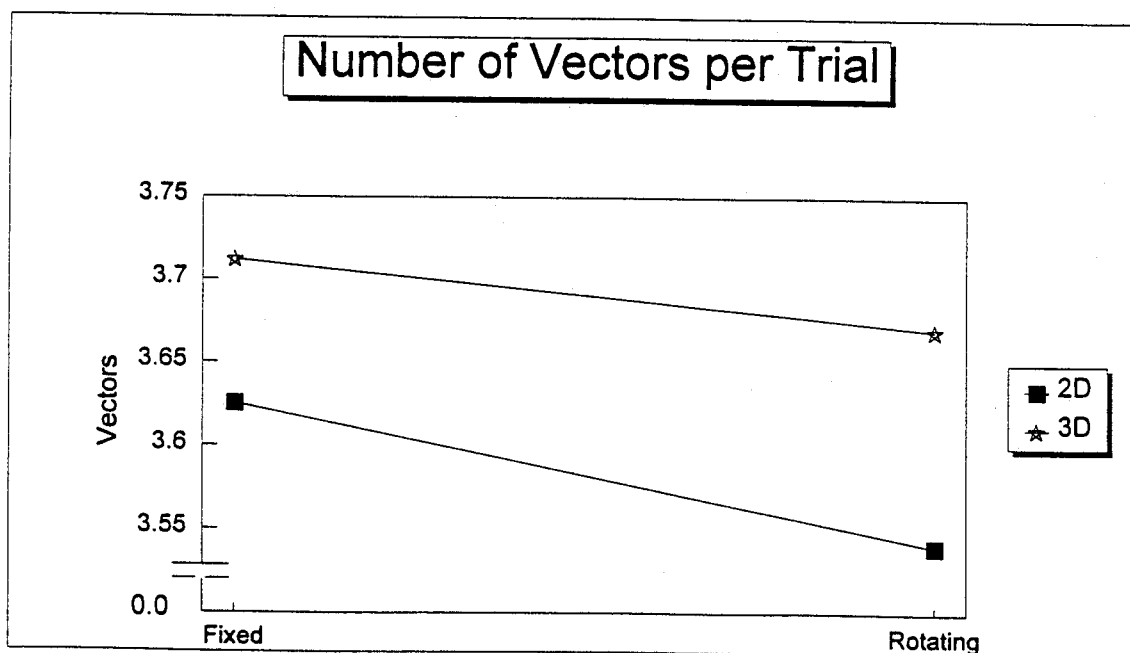


Figure 3.4: Number of vectors created for each condition type

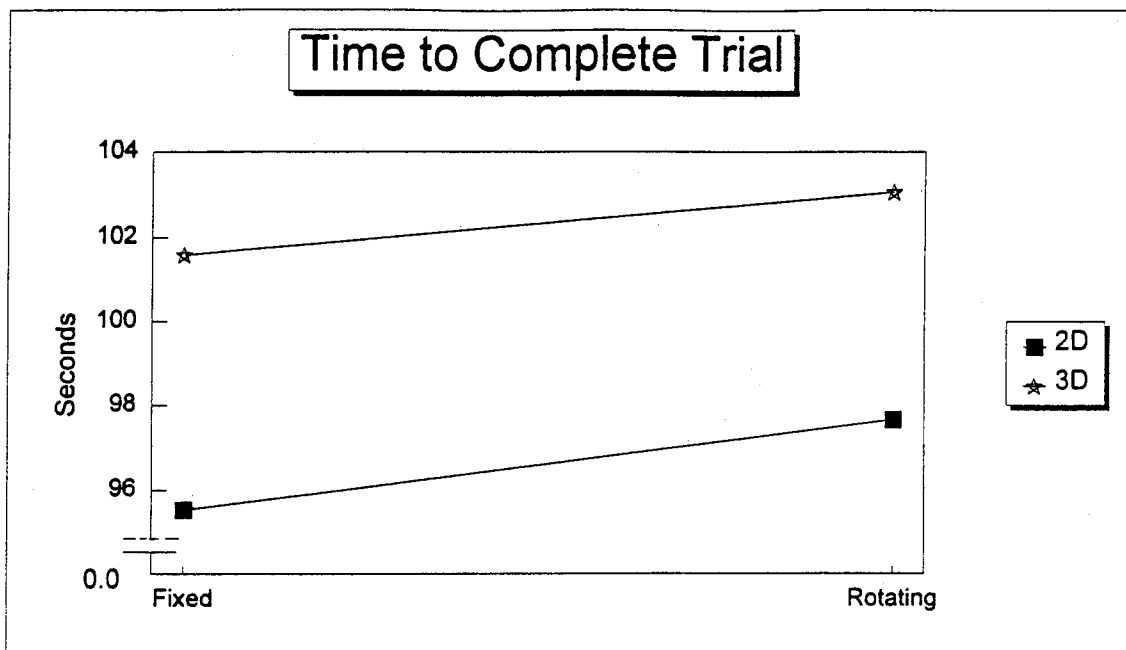


Figure 3.5: Time to complete trial for each condition

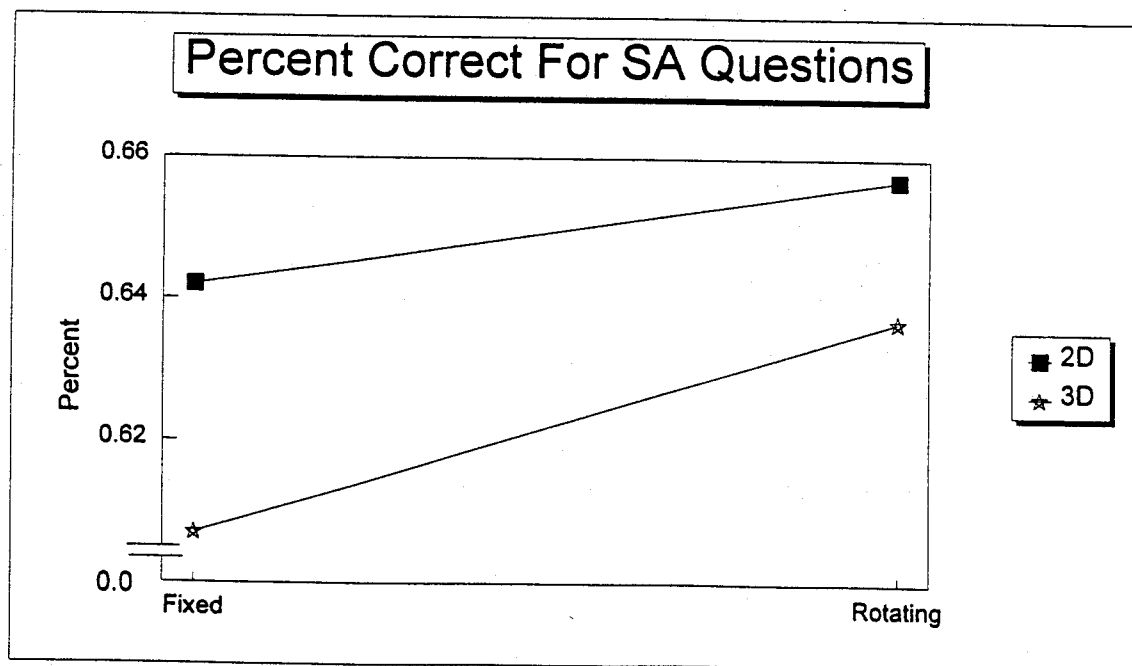


Figure 3.6: Percent correct for situational awareness questions

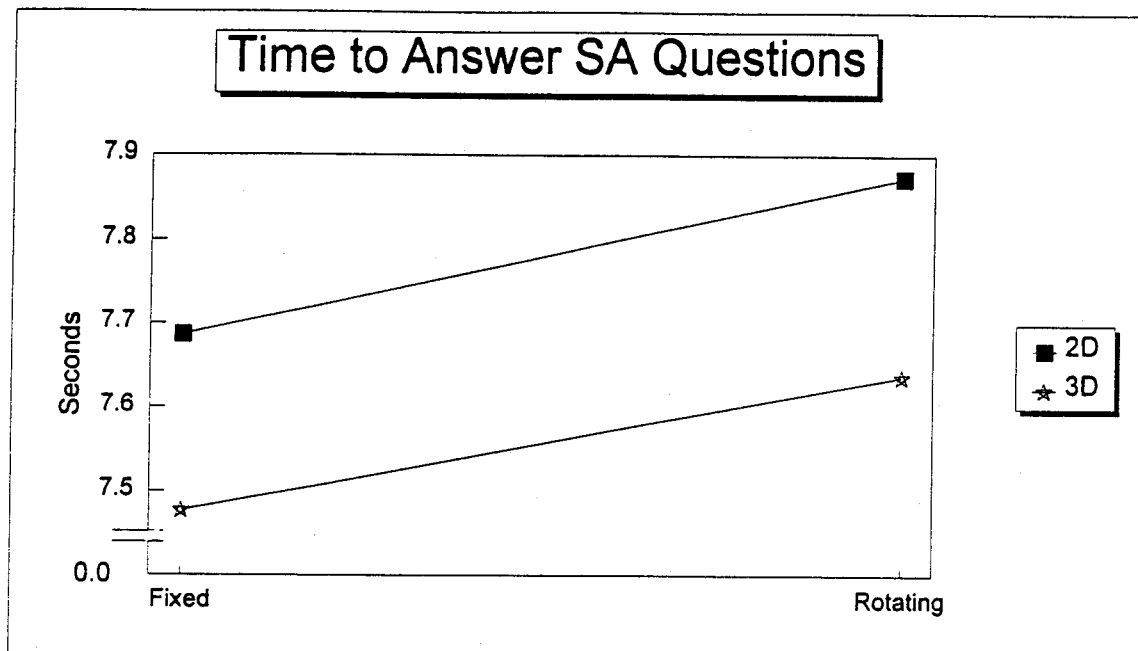


Figure 3.7: Time to answer situational awareness questions

Discussion

This experiment set out to examine the effects of display dimensionality and frame of reference rotation on a 3-D weather avoidance task. The primary factors that were evaluated included the distance traveled, contact with the weather formations, and situational awareness tasks. In the following we consider the effects of the two independent variables on performance, before offering some general conclusions.

Dimensionality

The effects of dimensionality showed mixed results as to its effect on the distance traveled by the pilots. The distance traveled in the radial and vertical planes in the present study, could be considered similar to the local guidance tasks evaluated in previous research. For the radial distance traveled, the 2-D displays showed significantly better performance shortening the path by approximately 2.5 miles out of 32 (or about 8%). This advantage for lateral navigation in the planar/profile display is consistent with the results found by Rate and Wickens (1993), and with results from studies of 3-D air traffic control displays revealing that perspective displays yield poorer performance on lateral estimation tasks (Tham and Wickens, 1993; Wickens and May, 1994). However, it differs from the results reported by Wickens et al. (1994) and Prevett and Wickens (1994), in that both studies found 3-D displays to support as good lateral tracking as 2-D displays. One factor that must be kept in mind is that the present study employed a 3-D tracking task and not a flight guidance task as used in previous research, and thus comparisons of differences or similarities with previous results must be viewed accordingly. In light of the unambiguous presentation of lateral error in the 2-D display, compared with the potential line-of-sight ambiguity on the axis in the 3-D display, it is easy to see how the latter led to greater time, less efficient planning, and longer routes than did the 2-D display.

In terms of the vertical distance traveled, neither display showed a significant advantage over the other. On the one hand, this finding differs somewhat from Ellis, McGreevy, and Hitchcock's (1987) examination of cockpit displays for traffic information which reported that pilots used more vertical maneuvers for aircraft

avoidance when using a 3-D display (although not necessarily better performance. On the other hand, the finding of no difference in vertical tracking is somewhat in contrast with results of Wickens et. al. (1994), Prevett and Wickens (1994), and Rate and Wickens (1993), who all found substantially poorer performance for vertical tracking in the 3-D displays.). In previous studies, the shortcomings of the 3-D display were represented by a cost to vertical deviations from the flight path, a nearly continuous sampling task. In the present study, the distance traveled was a consequence of decisions made only very intermittently (approximately 3-4 times/trial). It is possible then, that pilots chose to draw a new vector only at times when the vertical information was unambiguous; or, when it was ambiguous, they chose to resolve that ambiguity by constructing longer lateral paths, hence leading to the lateral path distance described above.

The penetrations of the weather formations was a variable designed to evaluate the ability of the display to present the weather to the user. Although results pointed toward an advantage for the 2-D display, dimensionality did not significantly influence the probability of coming into contact with a weather formation. Thus, while the 3-D display may have created some ambiguity of path trajectory relative to the weather, subjects apparently addressed this problem by conservatively selecting longer paths (in the lateral axis), and thereby increase their margin of safety.

The number of vectors created by the subjects was shown to be favored by the 2-D representation, but was not significantly affected by dimensionality. This measure was intended to reflect the subjects' general understanding of the nature of the weather, assuming that someone who was unclear of the location of the weather formations in the airspace would be forced to create more vectors to trace a path to the marker, where as a subject who had a good understanding of the airspace would be able to find a definite route through the weather, using a minimum number of vectors. Since neither type of displays showed significantly better performance it can be assumed that both type of displays reflected the weather information equally as well. Since our program did not compute an optimal "minimal path", we cannot say in an absolute sense whether the performance on both of the displays was good or poor.

The time to complete the trial is assumed to reflect both the distance traveled and the subjects understanding of the weather formations. Obviously the longer path taken to arrive at the marker (an effect observed with the lateral distance traveled) will result in a longer trial time; however, in addition to this, a longer time may also result from an individual spending extra time manipulating each vector within the 3-D space. Thus, the total time variable is probably the best measure of the general understanding of the nature of the weather formations, because a pilot with a good understanding of the weather (i.e. finding a clear path to the marker) would not require a long time to manipulate each vector. The results revealed that the 3-D display produced significantly slower trial times, a cost of about 6 sec (approximately 5%). The time penalty reflects three components: 1) the added distance traveled of the vectors (since longer vectors take longer to draw), 2) extra time manipulating, pointing, or aiming the vector, perhaps because the greater ambiguity of the 3-D display provided more of a time penalty than the need for scanning between the two panels in the 2-D display, 3) A time penalty for "twiddling" at the final goal point to terminate "right on" (more difficult in ambiguous 3-D). This third component was observed by Andre, Wickens, Moorman, and Boschelli (1991) who found the main penalty with the 3-D display.

Situational awareness also appeared to be unaffected by dimensionality in this study, although once again better performance was hinted at in the 2-D display. By supporting neither the 2-D display or 3-D this research is inconsistent with the results found by Rate and Wickens (1993) who found that a 2-D display supported better situational awareness. It also differs from research of Wickens et. al. (1994) and Prevett and Wickens (1994) who found that exocentric 3-D displays better supported the situational awareness tasks. The reason for these inconsistencies can most likely be explained by the fact that the situational awareness is extremely dependent on the nature of the task used to evaluate it, and the particular display being used. In particular, the results of the situational awareness task in this study may have been influenced by fact that since there was no set flight path to be taken, most of the questions were based on the starting position of the aircraft. Also, many of the subjects commented that since the weather formations were static, once an acceptable path was established, the need to "pay

attention” to weather formations that were not directly on or near this path was no longer needed. Many of these same reasons can be used to explain why dimensionality had no effect on the time to answer the situational awareness questions, and why the accuracy of these answers was relatively low.

In short, in terms of dimensionality it appears as if the 2-D displays showed an advantage in nearly every variable. However, only significant advantage over perspective displays were found for quicker navigation times and shorter lateral navigation distances, perhaps as a result of a conservative lengthening of the flight path which subjects adopted to deal with any ambiguity in the 3-D display. Other factors such as vertical distance, number of vectors, weather formation collisions, and situational awareness pointed toward an advantage for the 2-D display, but were not significantly different.

Rotation

The effects of map rotation on radial distance traveled, reflects what would have been expected by examining previous research, assuming there are similarities between the 3-D tracking task used here and a flight navigation task, used in previous research. In the present experiment it was found that the rotating display resulted in shorter radial distances than the fixed displays. This mimics the results reported by Wickens et. al. (1994), Rate and Wickens (1993), and Barfield, Rosenberg, Hans, and Furness (1992) in that the rotating or ego-referenced displays demonstrated better performance in the horizontal plane. This superior performance for the rotating display also indicates that the subjects may have been able to better understand the location of the weather in the rotating display, and thus were able to trace a shorter route. It is also possible that the magnitude of this effect might have been underestimated since a major portion of the traveling paths were along a generally northerly heading (where the two maps would not be expected to differ), given that all starting points were at the south end of the space and terminal points were at the north end.

For the vertical distance traveled it was shown that there was no difference between the track-up and north-up display. At first glance, this appears to conflict with the results reported by Wickens et. al. (1994) and Rate and Wickens (1993), who found

superior performance in vertical tracking for the rotating displays. However, in these studies the penalty for vertical performance was not due to a poor fixed map representation of the vertical plane, but was attributed instead to the resource cost of mental rotation for lateral judgment. In the present study, the costs of mental rotation were small (in that they didn't occur for much of the flight), and the magnitude of these costs to lateral flight distance were very small (less than 1 mile or 3%). Thus a great deal of extra resource costs to the vertical axis would not be expected.

Penetration of weather formations seemed not to be affected by the rotation of the display. Although there is no previous research in this area, it was expected from the other results (radial distance traveled) that by rotating the display the subjects would be able to better understand the nature of the weather formations in the airspace, and thus penetrate with the weather less often. However, as reported earlier it is possible that as a response to ambiguity in the fixed display pilots produced longer paths as a conservative and successful adjustment to avoid penetrations.

The number of vectors created by the subjects was also intended to reflect the ability of the display to portray the weather. As in with the penetrations of weather formations, no difference was found between the track-up and north-up displays. Thus, neither display supported production of a significantly clearer path through the weather formation to the marker.

Rotation of the display did not impact the time to complete the trial. This is a somewhat curious result, in it would be expected that a longer radial distance would be tied to a longer trial time. However, recall that the absolute difference in the path length between fixed and rotating was small and only of marginal statistical significance. It is thus easy to see how the small difference in time resulting for the slightly longer path adjustment, could render the effects of rotation on total time insignificant.

There was no difference between the two types of rotating displays for the situational awareness task. This finding is inconsistent with the inference proposed by Aretz (1991) and supported by Barfield, Rosenberg, Hans, and Furness (1992), that a fixed display will better support global situational awareness. However, these results do replicate the findings of Rate and Wickens (1993) and Wickens et. al. (1994), that a

track-up display is not detrimental to global situational awareness. This idea is also supported by a lack of significant difference between the time to answer the situational awareness questions. The experiment used a combination of ERF and WRF based questions that were not analyzed separately, and this may have played a defining role in these results.

General conclusions

We have found that the 2-D and rotating displays may offer superior performance in the distance of lateral route planning, and that 2-D displays will result in slightly faster weather planning times. Although most the factors (vertical distance traveled, penetration of weather, number of vectors, and situational awareness proficiency and latency) pointed towards an advantage for the 2-D display, there was no significant difference for display dimensionality or rotation for these measurements.

As mentioned earlier, this is the first examination of display dimensionality and frame of reference rotation for the presentation of weather in the cockpit. Other studies need to be conducted before any generalizations can be made for an operational system. Just as Wickens et. al. (1994) and Prevett and Wickens (1994), made improvements on the original displays for flight path guidance employed by Rate and Wickens (1993), further improvements need to be made to the displays used in the present study in order to properly evaluate the effects of dimensionality and rotation on weather presentation. As we elaborate below, three areas in particular could be improved to evaluate the display: 1) the use of a different 3-D tracking device; 2) including movement in weather formations; and 3) color coding weather formations for intensity or type.

First, some subjects found the combination of the joystick and button pushes to be awkward and complicated for the 3-D tracking tasks. A variety of 3-D tracking devices are available (i.e. space ball, hand trackers, and glove devices) and have been examined by researchers at the University of Toronto (Zhai & Milgram, 1993). It is possible that some of these might prove to be more compatible with the nature of the 3-D weather domain. Secondly, using static weather formations eliminates the fourth dimension of weather that must be considered: time. Weather is constantly moving and changing. Thus

to produce a display that is generalizable to the cockpit these factors need to be taken into consideration. In order to achieve an effective measure of global situational awareness, weather formations will need to be moving. Finally, not all weather is dangerous. Many of today's aircraft can easily penetrate weather with minimal hazard and save both time and money. Thus, an actual aircraft display could use color coding to differentiate weather intensity or type for pilots. Studies addressing these issues could lead to the further development of an effective weather display for future cockpits.

In conclusion, humans cannot change the weather. Therefore, the best we can hope to do in the aviation field is to understand the nature of the weather, detect it, and avoid it. To improve safety for all classes of aviation continued research needs to be conducted to improve the detection, assimilation, and presentation of weather to aviators.

Appendix A

Electronic Weather Planning Displays

[PLEASE READ THESE INSTRUCTIONS CAREFULLY]

The Reason : Presently, most pilots rely on raw radar returns, surface or pilot observations, and their own experience to interpret weather patterns and make operational decisions. It has been shown that this current system has limitations in both safety and effectiveness. In response, the FAA has set forth a modernization program which calls for better collection of weather data and improved dissemination of the data to pilots and controllers. You are participating in a beginning experiment to examine in what format this weather should be presented to the pilot to best support flying in hazardous weather conditions.

You will navigate through a total of 44 different weather scenarios. The first four will be practice runs, and during the next forty your performance will be recorded. There are four different types of displays that you will be navigating through.

The Task: In this experiment you will be expected to complete a fast route planning exercise, in which you will lay out a planned course through weather in both 3-D and 2-D display modes. To navigate through the space you will not actually "fly the aircraft" but will control a vector protruding from the nose of the aircraft, as if drawing a planned route through the weather on an electronic map. The joystick controls the position of the vector within space. Lateral deflections will change the heading of the of the vector, while for-aft deflections will control the rate of climb or descent of the vector. Pressing the trigger of the joystick will extend the vector from the nose of the aircraft, while pressing the trigger along with the Ctrl key will retract the vector. Once you are happy with the location and orientation of the vector and are ready to begin a new one, pressing the button on top of the joystick will move the aircraft along the vector and create a new vector. If you have moved the aircraft along a vector, and then realize that you are not

happy with it, you can backtrack by pressing the button and the Ctrl key at the same time. This combination will delete the previous vector that you have created. Your task is to navigate through the weather formations to the marker as quickly as possible taking the shortest possible route, without coming into contact with any of the formations. Also, while navigating through the weather remain aware of the various formations (i.e. their general size, height, and location).

The Displays: You will navigate through four different types of weather displays.

- 1) Three dimensional display with fixed background.
- 2) Three dimensional display with rotating background
- 3) Two dimensional display with fixed background
- 4) Two dimensional display with rotating background

In a rotating background your view point will always remain directly behind the aircraft. On the other hand, a fixed display will represent the display from the same view point through the entire trial. The task is the same for the different display types, however, the visual representations are what changes. The two dimensional display will depict a split screen with a top down view represented on the top portion and a profile view to represent altitude on the lower portion.

To Help You: There are several items added to this display that can aid you.

- 1) Every item on the display is tagged with its altitude. This includes the plane, the end of the vector, the marker, and all weather formations. On many of the weather formations the altitude is represented as a range from the lowest portion of the formation to the highest.
- 2) The aircraft, end of vector, and marker all have drop lines that can aid in establishing the exact location of these particular items.
- 3) If the drop line of the vector or the aircraft itself penetrate a weather formation they will change to the color of that formation.

- 4) The shadows on the ground created by the weather formations are representative of a shadow cast by a sun directly above.
- 5) While using the three-dimensional displays the viewing angled can be altered by plus or minus 15 degrees in order to reduce ambiguity. This can be accomplished with the use of the cursor keys (↑, ↓)
- 6) This display uses color depth cueing to aid in the perception of the location of objects. Thus, objects that are closer or nearest to you are more brightly colored while objects that are more distant will appear a darker color.

How You Will Be Assessed: The computer will record how long it takes you to complete each navigation task, the length of the vector created to reach the marker, if you come into contact with any weather formations or the ground, and how many times you are forced to backtrack or delete a vector. Also, at the end of each trial the computer will ask you a multiple choice question referring to the size height or location of a weather formation. The accuracy and time to respond to these questions will be recorded.

Note: Reaching the marker is not a precision navigation task. Due to the size of the initial vector and the imprecision of the joystick it may be difficult to end exactly on the marker. Thus get as close as possible in both location and altitude without doing a lot of final correcting and then press the Esc key. The computer will calculate the remaining distance from the aircraft to the marker. _

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